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MARINE CORPS LIGHT ARMORED VEHICLE AUTOMATED DATA COLLECTION ANALYSIS

by

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December 2010

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MARINE CORPS LIGHT ARMORED VEHICLE AUTOMATED DATA COLLECTION ANALYSIS

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ABSTRACT

This thesis describes the analysis of a Sense and Respond Logistics program as applied to the United States Marine Corps' Light Armored Vehicle. This program was initialized in 2003 by the Program Manger, Light Armored Vehicle in an effort to provide both users and commanders with real-time logistics information. This real-time information is collected from the Light Armored Vehicle via sensors that are placed in critical areas. The analysis carried out for this thesis centers upon the data collected from the aforementioned sensors during Phase II and Phase III of the overall program. The sensor data is compared to normal operating parameters for the respective component. The data collected in Phase II is also compared with Phase III. Most of the data from both phases falls within normal limits, 77% and 63% respectively. However, there is evidence to suggest a statistical difference between Phase II and Phase III. Due to the lack of baseline data, it is impossible to determine which phase is more accurate. Only nonparametric methods are used in this analysis.

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EXECUTIVE SUMMARY

One of the biggest lessons learned from Desert Storm and Operation Iraqi freedom was the Marine Corps' way of "doing logistics" was outdated and inefficient at best. In an effort to modernize logistical operations after Desert Storm, the Marine Corps chose a group of systems collectively known as Global Combat Support Systems-Marine Corps (GCSS-MC). GCSS-MC is divided into two major areas: GCSS-MC Logistics Chain Management (GCSS-MC LCM) and GCSS-MC Logistics Command and Control (GCSS-MC Log C2). The focus of this thesis is upon one aspect of GCSS-MC Log C2 called Sense and Respond Logistics (S&RL).

Sense and Respond Logistics incorporates real-time logistics information to provide both users and commanders with an accurate readiness posture. For example, mission critical information such as vehicle health and performance is passed on to pertinent decision makers in time to make effective decisions. The information about vehicle health and performance is gathered by applying various sensors to the vehicle platform. This research project considers the data collected from sensors applied to the United States Marine Corps' (USMC) Light Armored Vehicle (LAV). A literary review was conducted prior to this study. While sensors have been applied to a wide array of both ground and air platforms, those studies are not fundamentally relevant for this work. This study is unique in that there is no baseline data from which concise conclusions can be drawn.

In order for the data collected from the aforementioned sensors to be useful, the data must be

accurate. In order to measure accuracy of sensor reported data, a baseline must be used. In the absence of a baseline, as is the case here, normal operating ranges as established by the LAV vehicle Technical Manuals (TM) are used to assess sensor performance.

The analysis presented here focuses on the data from two different phases (phases II and III) of the S&RL program, as applied by the Program Manager, LAV, to the LAV platform. However, the two phases are not equal in stature. There are more LAVs included in phase II, but fewer sensors; whereas there are fewer LAVs in phase III, but more sensors. With this in mind, the overall percentage of data which is reported within normal operation parameters is 77% from phase II, and 63% from phase III. Thus, the response to the question of whether the processes by which data are collected are reporting values within normal operating parameters is, in general, yes.

A comparison is also made between sensors of each phase. There are four sensors in phase II that collect the same information as in phase III. So, the percentage of data that falls within normal operating parameters for these four sensors is compared directly from phase II with phase III to ascertain whether a statistical difference exists between the two phases. The results revealed a statistical difference between two of the four sensors. Without baseline data, it is impossible to determine which phase is more accurate. Therefore, future studies must determine and include baseline data. All of the analysis carried out is nonparametric in nature as the assumption of normality could not be made.

LIST OF ACRONYMS AND ABBREVIATIONS

AL	Autonomic Logistics
ATLASS	Asset Tracking and Supply System
DTC	Diagnostic Trouble Code
FMF	Fleet Marine Force
CSS	Combat Service Support
EPLS	Embedded Platform Logistics System
ECM	Engine Control Module
GCSS-MC	Global Combat Support Systems—Marine Corps
GCSS-MC LCM	Logistics Chain Management
GCSS-MC Log C2	Logistics Command and Control
JAMISS	Joint Asset Management Information Support System
LAV	Light Armored Vehicle
LAVTC	Light Armored Vehicle Training Company
MCLB	Marine Corps Logistics Base
MIMMS AIS	Maintenance Management System Automated Information System
NSWC	Naval Surface Warfare Center
NMCI	Navy Marine Corps Intranet
OBC	On-board Computer
OEM	Original Equipment Manufacturer
PM	Program Manager
PMLAV	Program Manager Light Armored Vehicle
RCM	Reliability Centered Maintenance
RIT	Rochester Institute of Technology
S&RL	Sense and Respond Logistics
SOI	School of Infantry
SME	Subject Matter Expert
SASSY	Supported Activities Supply System

SPN	Suspect Parameter Number
TM	Technical Manual
USMC	United States Marine Corps
XML	Extensible Markup Language

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I. INTRODUCTION

A. LOGISTICS MODERNIZATION BACKGROUND

One of the biggest lessons learned from Desert Storm and Operation Iraqi Freedom was that the Marine Corps' way of "doing logistics" was outdated and inefficient at best. With the high operational tempo of the modern battlefield, these antiquated systems and procedures did not sufficiently meet the needs of the battlefield commander or those in support of the commanders. This support system consisted of a conglomeration of "stove pipes," or information channels that kept programs from communicating with each other as well as prohibiting data integration. The bottom line was inefficient and unpredictable support. As a result of this unpredictability, "mountains" of supplies often were pushed forward in an effort to meet whatever need arose. This method had been used for decades and is nonoptimal, impractical, and expensive. To that end, and to improve their logistics support, the Marine Corps sought a solution to provide the appropriate level of logistics support for the modern war fighter.

B. GLOBAL COMBAT SUPPORT SYSTEMS—MARINE CORPS

Global Combat Support Systems—Marine Corps (GCSS-MC) is the means by which the Marine Corps is now modernizing its logistics. GCSS-MC is "a portfolio of systems that support logistics elements of command and control, joint logistics interoperability, and secure access to and visibility of logistics data" (Anthes, 4). GCSS-MC is made up of two integrated systems: GCSS-MC Logistics Chain Management (GCSS-MC LCM) and GCSS-MC Logistics Command and Control (GCSS-MC Log C2).

1. GCSS-MC LCM

Logistics Chain Management is the first part of GCSS-MC. When fully implemented, GCSS-MC LCM will replace legacy systems currently in use. GCSS-MC LCM will provide a modern, web-based supply network that is fully integrated with both supplier and consumer. The legacy systems currently in use are: Maintenance Management System Automated Information System (MIMMS AIS), Supported Activities Supply System (SASSY) and Asset Tracking and Supply System (ATLASS) (Delarm and Rackham, 2).

a. MIMMS AIS

MIMMS AIS is an interactive electronic platform that gives commanders a maintenance posture overview. The goal of MIMMS AIS is increased equipment readiness. This platform allows both MIMMS Clerks and mechanics to use a standardized format from which to conduct administrative maintenance actions (USMC Student Outline MIMMS, III-2).

b. SASSY

SASSY is a stationary, centralized, mainframe-type platform system that is used to manage supplies. SASSY acts as the “accountant” and primary records keeper for stock management and supply forecasting (USMC Student Outline, 2). SASSY “balances the books” on a daily basis, reducing the administrative burden and errors normally associated with stock control.

c. ATLASS

ATLASS (I, II+) is a deployable version of SASSY. For example, Fleet Marine Force (FMF) units, at the using unit level, maintain an ATLASS machine, which interacts with SASSY via a daily data file. This data file is submitted electronically and is called a courier. ATLASS is used for both requisitions and supply management at the unit level. SASSY is used at the base or regional level. ATLASS files should match SASSY files with SASSY acting as the “boss” or master file (USMC Student Outline, 2).

2. GCSS-MC Log C2

Log C2 is the second part of GCSS-MC. Log C2, when fully implemented, will enable command and control support that is fully automated and integrated. The goal is “increased effectiveness of the force through enhanced friendly situational awareness and Combat Service Support (CSS) planning and decision making” (Delarm and Rackham, 2).

The focus of this thesis is to study one aspect of this GCSS-MC LCM/Log C2 transformation: Sense and Respond Logistics (Lusardi, 8).

C. SENSE AND RESPOND LOGISTICS

In an effort to provide real-time logistics information to both users and commanders, Autonomic Logistics (AL) is used. As a comparison, modern automobiles provide real-time information about current conditions using various electronic sensors to the automobile’s onboard computer. The computer can then use this information to do things like adjust air/fuel intake to change performance or emissions. Autonomic Logistics[1] provides similar visibility, but on a larger scale. For example, AL can track mission-critical information such as vehicle health and performance, and does so via sensors. This data is then transmitted across a communication infrastructure into the GCSS-MC system. This information can therefore be monitored in real time to give commanders and logisticians the ability to sense the needs and then respond accordingly.

Sense and Respond Logistics (S&RL) provides a vastly superior view of logistical posture and needs over current legacy systems. This thesis focuses on S&RL as it is applied to the Light Armored Vehicle (LAV) (see Figure 1).

[1] It should be noted, however, that "Autonomic Logistics" is used here to describe a process, and not in reference to the Marine Corps' program of record, Embedded Platform Logistics System (EPLS), which is managed by the Program Manager (PM), Autonomic Logistics.

Figure 1. LAV-25 (From Mislick, 2010)

D. SENSE AND RESPOND LOGISTICS AND THE LAV

As new technologies have developed on the commercial market, modern maintenance practices have been streamlined. Two efficient methods of logistics management, that have enabled managers to refine practices in order to reduce operating and support costs, are “just in time” delivery and “condition based maintenance” (Sanchez, 5). Just in time delivery refers to a business philosophy that sees maintaining an inventory as a waste of money. Just in time delivery is succinctly described as “the right material, at the right time, at the right place, and in the exact amount.” Conversely, condition based maintenance is a style of maintenance that anticipates failure, rather than waiting for failure. By using health-monitoring devices, maintenance can be performed when these devices indicate an impending failure or performance degradation. In 2003, the Program Manager (PM) for the LAV (PMLAV) began to investigate how these modern practices could be integrated into the LAV program. The goal was “to investigate the feasibility and economics of incorporating Sense and Respond Logistics, Condition Based Maintenance and other related initiatives into an effective Enterprise Life Cycle Management Tool” (Program Manager Light Armored Vehicle, 2). An important aspect of these “other related initiatives” is vehicle asset health monitoring. This health monitoring enables all parties involved, from the maintainer to the Program Manager, to fully integrate maintenance efforts. This joint effort ensures that the lifespan of the vehicle is maximized without robbing the commander of readiness. An example of this is replacing the part or component prior to failure rather than waiting for failure to occur. The initial effort of vehicle asset health monitoring, called Phase I, began in November 2003 (Program Manager Light Armored Vehicle, 2).

1. Phase I

The intent of Phase I by PM LAV was primarily feasibility. The questions asked were (1) “Can vehicle health monitoring be incorporated into the LAV platform?” and, if so, (2) “How much will it cost?” The effort was collaborative in nature and involved PM LAV, Marine Corps

Logistics Base (MCLB) Albany, Georgia; Anniston Army Depot, Anniston, Alabama; Delphi Automotive Cubic Systems, Troy, Michigan; Portal Dynamics, Warren, Michigan; Rochester Institute of Technology (RIT), Rochester, New York and Applied Research Laboratories at Pennsylvania State University, State College, Pennsylvania.

The work done by this collaborative team yielded two LAVs, in December 2004, outfitted with various sensors, which fed the recorded information to a data bus that could communicate wirelessly. This proof of concept effort was a success and showed “substantial value” (Program Manager Light Armored Vehicle, 5) to all interested parties. The recommendations from this phase primarily revolved around refining the previously developed procedures. Phase II incorporated several of these refinements.

2. Phase II

Phase II of the project began in November 2005 and focused on infrastructure improvements as well as health monitoring refinements. Once the data was collected from these refined sensors, an improved wireless transfer system was developed in order for interested parties at all levels to have quick access to the data. This characteristic enables both the maintainer and the subject matter expert (SME) to see the information and collaborate if necessary on the proper course of action. The medium used to convey the data to all interested parties was the Joint Asset Management Information Support System (JAMISS) (Naval Surface Warfare Center, 6).[2]

In order to determine the best locations to install sensors, as well as which faults to monitor, PM LAV initiated a Reliability Centered Maintenance (RCM) program. RCM is a process by which vehicle performance is ensured, based on the vehicle's current readiness posture. These sensors, as well as an onboard computer, new data bus, instrument cluster and a wireless transmission device, made up the final prototype of the complete health monitoring system.

The health monitoring system was installed on a prototype LAV by Technical Services, Inc, Syracuse, Indiana. After the prototype installation, 11 complete systems were sent to the LAV training company (LAVTC) at the School of Infantry West (SOI West), Camp Pendleton, California, for installation on nine other LAVs. In total, ten LAVs were outfitted with the phase II system and two complete systems were provided for replacement parts.

Training was conducted at the LAV schoolhouse for users and maintainers alike. Operational testing began to fully integrate the Marines and the LAV with the health monitoring system. As the data was collected, upper and lower bounds were established for normal operating ranges. These ranges were obtained from similar commercial applications as well as the LAV technical manual (TM). Data

[2] JAMISS is a web-based, single point interface into which the data is transferred. JAMISS not only allows access to the data, but also maintains historical records of various LAV components.

collected that was outside the upper and lower bounds was studied for accuracy. Various quantitative techniques were applied to correct the deficient data.

At the end of this phase, in March 2007, all goals had been met and a functional vehicle health monitoring system was in place, but improvements were still necessary. Phase III further refined and streamlined the system.

3. Phase III

Concluding that the system developed in Phase II was too complex, complexity was reduced in Phase III while still maintaining functionality (Naval Surface Warfare Center, 3). This functionality, maintained on four LAVs that were not part of Phase II (see Figure 2), consists of data collection on board the LAV as well as the wireless transfer of this data to a server inside the LAVTC maintenance building. Once in the server, the data was originally linked directly to Crane, but Navy Marine Corps Intranet (NMCI) network security concerns prohibited the direct transfer of data. Currently, the data is transferred manually from the server at LAVTC to the servers at Crane.

Phase II	Phase III
521363	521661
521485	521683
521563	521753
521441	521767
521689	
521471	
521417	
521366	
521516	
521749	

Figure 2. LAV serial numbers by phase

The overall improvements in Phase III consisted of an improved wireless network; the onboard computer was replaced by a black box to reduce complexity; and all components were ruggedized, bringing the system closer to military specifications.

This thesis encompasses how the data was collected as well as exploring the quality of the data.

E. SCOPE OF THESIS

The scope of this thesis concerns the accuracy of the data collected in Phase II and Phase III. In order for this program to be effective, the data collected must be accurate before it is used and subsequently deposited into data storage. Therefore, the primary questions asked by this thesis are:

(1) Are the processes by which data are collected recording values within normal operating parameters?

(2) If errors are introduced into the data, is there any indication as to where this takes place?

(3) Are there differences between the data collected in Phase II and Phase III?

(4) Are there similarities or correlations between the two data sets?

The analysis presented in this thesis is intended to provide a better understanding and overview of the combined efforts of many organizations. The end result of this study, in combination with other similar studies, is to develop a systematic approach to data collection that is accurate and can be applied to various other platforms. The accuracy of the data collected and stored is paramount to effective Total Lifecycle Maintenance Management and cost reduction.

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II. DATA AND METHODOLOGY

A. SENSOR OPERATION

The overall concept of data collection and health monitoring has several facets. The first is to provide operators with real-time performance information. The second is to provide those that maintain the vehicles with better insight, as well as advanced knowledge, of potential problems. The third is to allow greater performance visibility above the organizational level. However, the overall goal is to improve the quality and accuracy of maintenance data that is collected.

1. Method Overview

In order to achieve proper and accurate monitoring, sensors are applied to the vehicle platform. Some of the sensors collect data directly whereas other sensors process data indirectly. For example, the planetary gear sensors are placed directly on the planetary hub and transmit the information to the On-board Computer (OBC). Sensors that collect data indirectly, like engine oil pressure for example, monitor information provided to the oil pressure gauge from the Original Equipment Manufacturer (OEM) sensors. A study carried out by the Applied Research Labs at Pennsylvania State University determined where these sensors should be placed on the LAV (Program Manager Light Armored Vehicle, 5).

2. The Specific Process

The sensors monitor a particular parameter and transmit this information to the Engine Control Module (ECM). The ECM keeps track of reported data using the sensor’s Suspect Parameter Number (SPN). SPNs are reference numbers assigned to each sensor to simplify data collection. The ECM incorporates any correcting methods developed by Delphi and Solidica that are needed to ensure the accuracy of the data. Once corrected, the ECM checks this information against pre-established ranges. If the sensor is reporting data that is outside of normal operating ranges, the ECM reports a Diagnostic Trouble Code (DTC). The DTC can be in one of three category levels: minor, moderate or severe. This information is then communicated to the driver by way of signal lamps. The speed at which the signal lamp flashes indicates the severity of the error. Thus, the faster the light flashes, the farther outside normal operating parameters. Figure 3 shows the signal lamp panel as the driver sees it. Figure 4 shows the signal lamp panel’s placement on the annunciator panel.

Figure 3. Signal lamp panel (From U.S. Marine Corps, 2009).

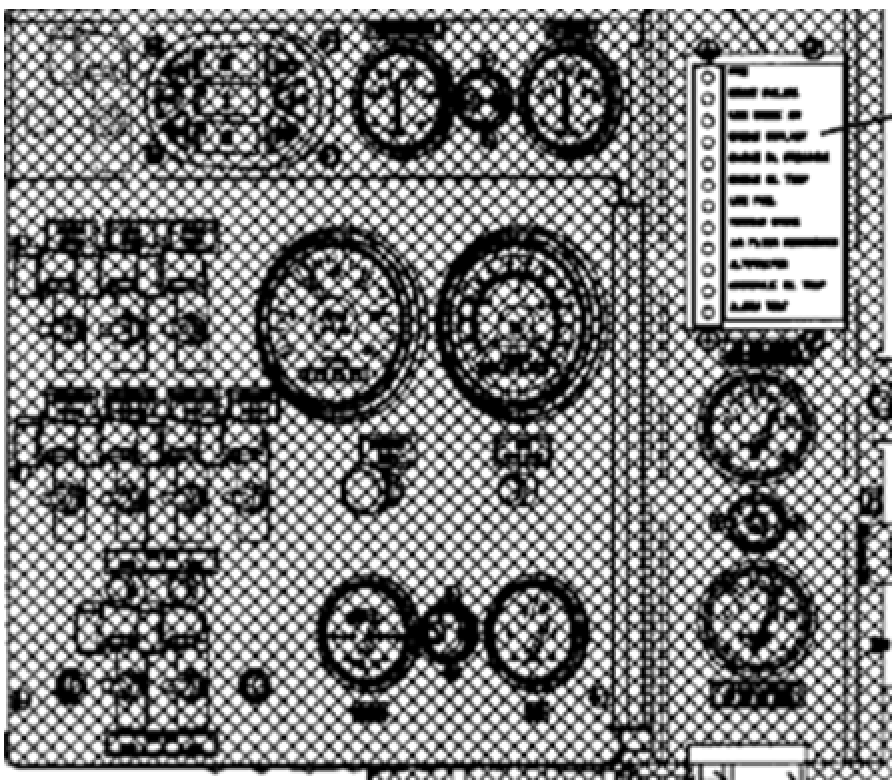

Figure 4. Signal Lamp Panel's location within the Annunciator panel (From U.S. Marine Corps, 2009)

However, all sensors are not fault-monitoring sensors. For example, the engine hours sensor is not fault related, so a DTC is never reported.

As DTCs are reported for fault-monitoring sensors, they are recorded in the OBC. The OBC transmits all recorded data to the server inside the maintenance bay via wireless network.

This section outlines how data is reported and recorded for use via sensors. As mentioned in Chapter I, not all sensors included in Phase II were transitioned to Phase III. Table 1 presents all sensors in SPN order for both phases. The highlighted sensors are the only ones that were included in both phases. However, there are five sensors for which neither data was collected nor a sensor description included with the other sensor’s descriptions (see Appendix A for sensor descriptions from Enterprise Server data).

SPN	Sensor Description	Phase II	Phase III
84	Wheel speed	Yes	Yes
96	Ratio of fuel level to volume of tank	Yes	Yes
100	Engine oil pressure	Yes	No
102	Turbo Boost	Yes	No
106	Air Inlet Pressure	Yes	No
108	Barometric pressure	Yes	No
110	Engine Coolant Temperature	Yes	Yes
114	Battery current	Yes	No
115	Alternator Current	No	Yes
158	Battery voltage switched	Yes	No
165	Compass Heading	No	Yes
167	Alternator Voltage	No	Yes
168	12V Battery voltage	Yes	No
171	Ambient air temperature	Yes	No
175	Engine oil temperature	Yes	No
177	Transmission oil temperature	Yes	No
190	Engine speed	Yes	Yes
245	Odometer	No	Yes
247	Engine Hours	No	Yes
517	GPS Vehicle Speed	No	Yes
584	Latitude	No	Yes
585	Longitude	No	Yes
703	Mission Reset	Yes	No
707	Master Warning Lamp	Yes	No
708	Parking Brake Lamp	Yes	No
709	Brake Lamp	Yes	No
711	Low Brake Air Lamp	Yes	No
716	Fire Lamp Indicator	Yes	No
1087	Air Pressure 1	No	Yes
1088	Air Pressure 2	No	Yes
1638	Hydraulic oil temperature	Yes	No
1762	Hydraulic pressure	Yes	No
1800	Battery temperature	Yes	Yes
1801	In dataset, no description available	No	Yes
9000	Battery 1 State of Charge	No	Yes
9001	Battery 1 State of Health	No	Yes
9002	Battery 3 and 4 Current	No	Yes
9003	In dataset, no description available	No	Yes
9004	In dataset, no description available	No	Yes
9005	Battery 4 Voltage	No	Yes
11800	In dataset, no description available	No	Yes
11801	In dataset, no description available	No	Yes

Table 1. Phases II and III sensor list

B. DATA PROCESSING

The Naval Surface Warfare Center (NSWC) in Crane, Indiana maintains the database where all of the sensor data ultimately is stored. The data used for this thesis was obtained from NSWC via copies of these database files. The files were divided between Phase II and Phase III data.

1. Phase II Data

The Phase II data consists of three elements: (1) On-Board Computer (OBC) Extensible Markup Language (XML) files, (2) Pre-correction files and (3) Post-correction files. The OBC files contain the sensor data, as it was stored on the specific vehicle before wireless transmission to the server. If transmission errors do not exist, these files should match exactly what is stored in the NSWC database.

One of the tasks from Phase II was to cleanse or correct any sensor readings that were not accurate. The pre-correction files are the files containing the raw data in its uncorrected form. The Post-correction files contain the data collected after the correction and cleansing methods were applied. Figure 5 shows an example of the Pre/Post cleansing database file data point used for this analysis. The column values are as follows: (1) LAV Serial Number, (2) Year, Month, Day, Hour, Minute and Second, that the sensor reported the data (3) The Suspect Parameter Number (SPN), a distinct number that represents a specific sensor and (4) The value reported by the sensor. This thesis focuses on the uncorrected data from Phase II, which was the only usable data set provided for phase II analysis by NSWC.

LAV Serial Number	Date/Time Stamp	SPN	Value
521363	2006-06-29 06:33:25.843000000	110	37

Figure 5. Phase II database data point

2. Phase III Data

The Phase III data consists of a single file of corrected data. An example of a Phase III data point used for analysis is shown in Figure 6. The column values are as follows: (1) The LAV serial number, (2) The Suspect Parameter Number is a distinct number that represents a specific sensor, (3) The float value is the value reported by the sensor and (4) The Year, Month, Day, Hour, Minute and Second that the sensor reported the data (Float Value).

LAV Serial Number	SPN	Float Value	Create Date
521661	84	0	2009-05-22 10:11:52.027000000

Figure 6. Phase III database data point

3. Preprocessing

Due to the size and length of these database files, preprocessing of the data was required. A sorting program, written by the author using Java (Oracle, 2010) for this research project, is used to separate the master files into specific vehicle and sensor files. Additional sensor files were created that contained all of the data for a specific sensor across all ten LAVs. However, several of these constituent files were still too large to manage effectively.

As can be seen from Figures 5 and 6, a database row is a string, which consists of five to eight elements. Since the sensors can report data in microsecond intervals, the number of rows can become quite numerous. For example, several of the files have several million rows of data. However, since the sensors report data in microsecond intervals, there are many data points per second. For the purposes of this thesis, larger time intervals such as 5 to 10 seconds are acceptable. Microsecond readings do not add specific granularity that is useful for this thesis. So, in order to manipulate and process this data efficiently and timely, a method was developed to put these rows into larger time interval bins to shrink the file size while maintaining as much data as possible. The overall benchmark was to reduce the file size to less than three megabytes. Otherwise, the date conversions, as mentioned in subsequent paragraphs, became too cumbersome and time consuming. For example, a 25-mega-byte file needed to be reduced to less than three megabytes, or 1/10 of the original size. So, the java sorter averages the sensor data for every ten rows and then writes this row to a separate file, thereby reducing the file size to 2.5 megabytes. Although some data granularity is lost because of this process, the overall processing functionality gained is more valuable.

In order to effectively compare sensor readings in time, the time elements in the row strings depicted in Figures 5 and 6 were parsed and converted to numeric objects. A converting function, written by the author for this research project using R (R Development Core Team (2010)), converts the date/time elements into three separate columns of data. Figure 7 depicts a typical data point used for analysis after the time conversion has been applied. The column values added by the conversion program are Numeric Date, Numeric Time and Cumulative Time. The numeric date is a character representation of the object "2006-08-02” that can be used for analysis. The numeric time is the numeric value of “10:24:44” in seconds. The cumulative time is the numeric date converted into seconds and then added to the numeric time. This process allowed the data from different sensors to be compared in the same time frame using the cumulative time.

Serial Number	Date/Time Stamp	SPN	Value	Numeric Date	Numeric Time	Cumulative Time
521689	2006-08-02 10:24:44.667000000	110	71	13362	37484	1154514284

Figure 7. Data point with time conversion output

4. Methodology

In order to assess sensor accuracy, a baseline measurement that is accurate must be used. However, in the absence of this, (as is the case with this thesis) all sensors are evaluated based on normal operating ranges as established in the Technical Manuals (TMs) (see Appendix B). Thus, each sensor reports a measurement of a parameter that is either within normal operating ranges or not. The readings that fall on or within the operating parameters are considered within standards; otherwise, outside standards. This method provides a ratio of data points within standards to total data points from which other sensors are compared.

Phase II has its own suite of sensors from which six were deemed worthy of inclusion into the Phase III sensor suite. Analysis of the nonworthy sensors from Phase II is left for future analysis. The analysis carried out in this thesis focuses on the sensors from Phase III for which a normal operating range is established from the TM as well as the six worthy sensors from the Phase II sensor suite. Figure 8 shows the complete list of sensors for which data was collected. The six common sensors between Phase II and Phase III are highlighted.

SPN	Sensor Description
84	Wheel speed
96	Ratio of fuel level to volume of tank
110	Engine Coolant Temperature
115	Alternator Current
165	Compass Heading
167	Alternator Voltage
190	Engine speed
245	Odometer
247	Engine Hours
517	GPS Vehicle Speed
584	Latitude
585	Longitude
1087	Air Pressure 1
1088	Air Pressure 2
1800	Battery temperature
9002	Battery 3-4 Current
9005	Battery 4 Voltage
15092	Fuel Pump 1 (pump 2 in phase II)
15093	Fuel Pump 2
19002	Battery 3-4 Current
19005	Battery 3 Voltage
29005	Battery 2 Voltage
39005	Battery 1 Voltage

Figure 8. Sensors used in analysis

All analysis carried out on both phases of data is nonparametric in nature, with no assumption made as to distribution type. Specifically, the assumption of normality could not be made. Specific vehicles are looked at individually for any trends or errors that may exist within that vehicle's sensor suite. Sensors results are then compared across vehicles in the same phase and then across phases for an overall posture assessment.

5. Assumptions

The primary assumption made for this analysis concerns vehicle operation. It is assumed that during the data recording periods, the vehicles are operating normally. Thus, any data that is reported outside of normal operating parameters can be attributed to sensor error and not an actual vehicle in need of repair. It is also assumed that the vehicles are all used in basically the same manner. Thus, the differences in how the vehicles were operated and the terrain over which they drove are negligible.

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III. ANALYSIS

A. INTRODUCTION

As previously mentioned in Chapter II, and before analysis could begin, a significant amount of data preprocessing needed to be performed to reduce the file sizes. Once the file sizes were reduced to less than 3 MB, the data/time stamp was converted to a numeric value rather than a string.

With pre-processing complete, the analysis is carried out by phase. That is, Phase II analysis is carried out first, followed by Phase III. The Phase II data files consist of only uncorrected data; data for which correction algorithms and scaling factors have not yet been applied. The Phase III data files used for analysis are corrected.

Within each phase, the data are analyzed by LAV serial number. The complete list of serial numbers is located in Figure 2.

As each LAV is analyzed, the initial step of analysis involves plotting the LAV wheel speed over time. Figure 9 depicts the wheel speed over time and shows distinct data recording periods. Some periods record motion and others do not. Thus, the files are split into distinct periods to capture motion. With the data files split into moving (dynamic) and stationary (static) sections, statistics are collected on both dynamic and static files as well as the total file (static and dynamic files together). Preprocessing and analysis yield three distinct files. From these three distinct files, statistics are collected for all the sensors (see Appendix C for data collection samples) listed in Figure 8.

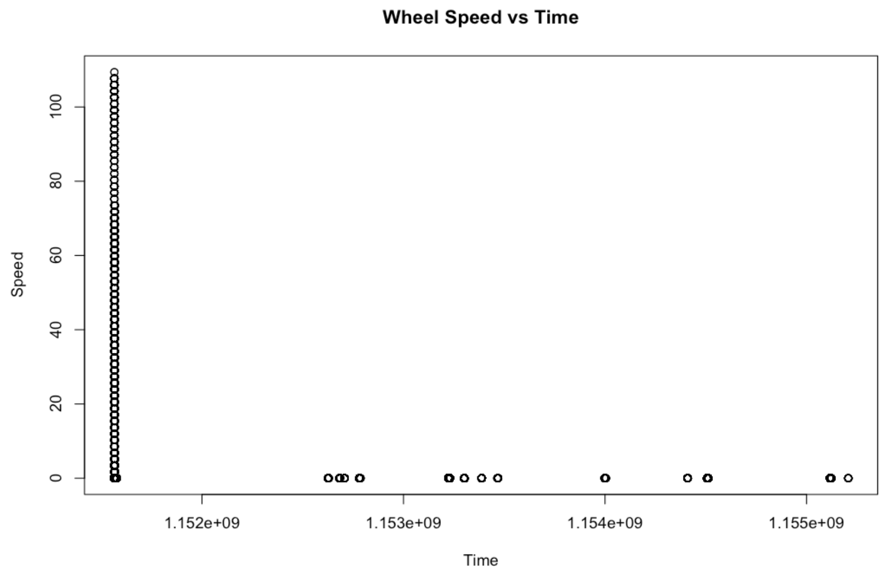

Figure 9. Wheel speed vs. time plot

B. PHASE II UNCORRECTED DATA ANALYSIS BY LAV SERIAL NUMBER

1. LAV Number 521363

The only problem discovered with this LAV involves the fuel sensor. The analysis of the stationary cool down period reveals a fluctuation of fuel level while the engine is neither running nor the vehicle moving. As can be seen from the upper plot in Figure 10, the engine speed is zero; so, it is not running. The middle plot in Figure 10 depicts the engine cooling down. However, the third plot in Figure 10 depicts the aforementioned fuel level fluctuation, primarily decreasing, while the engine is not running. Although these changes could be attributed to fluid movement as the vehicle’s motion stopped, the timeframe over which the data is captured is 20 minutes. It is excessive to assume that the kinetic energy carried by the moving fuel would dissipate this slowly after vehicle movement ceased.

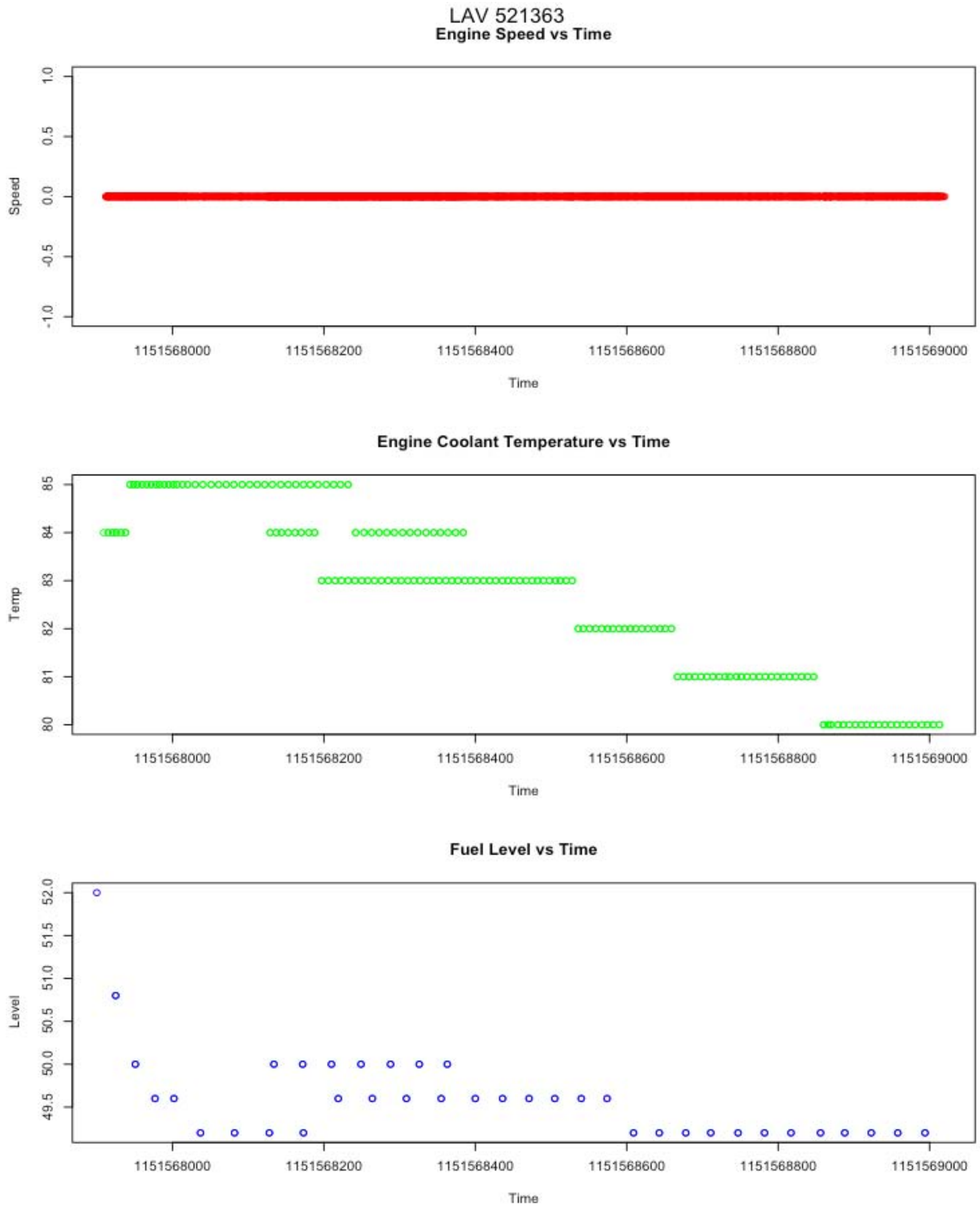

Figure 10. Fuel level fluctuation

2. LAV Number 521441

An abnormality discovered on this LAV comes from the fuel level sensors. The upper plot in Figure 11 shows the wheel speed. The wheel speed plot looks like normal operations. The third plot, which depicts engine coolant temperature, also shows normal operations. However, the middle plot depicts the fuel level concern. Based on the wheel speed and the engine temperature, the LAV is carrying out normal operations. The fuel level plot shows a decline that does not fit with previous data in the same plot. The normal fluctuation of fuel levels over various terrain seems well depicted early in the plot. However, the latter decline of approximately 40 gallons does not seem appropriate when normal operation prior to this did not consume that much fuel.

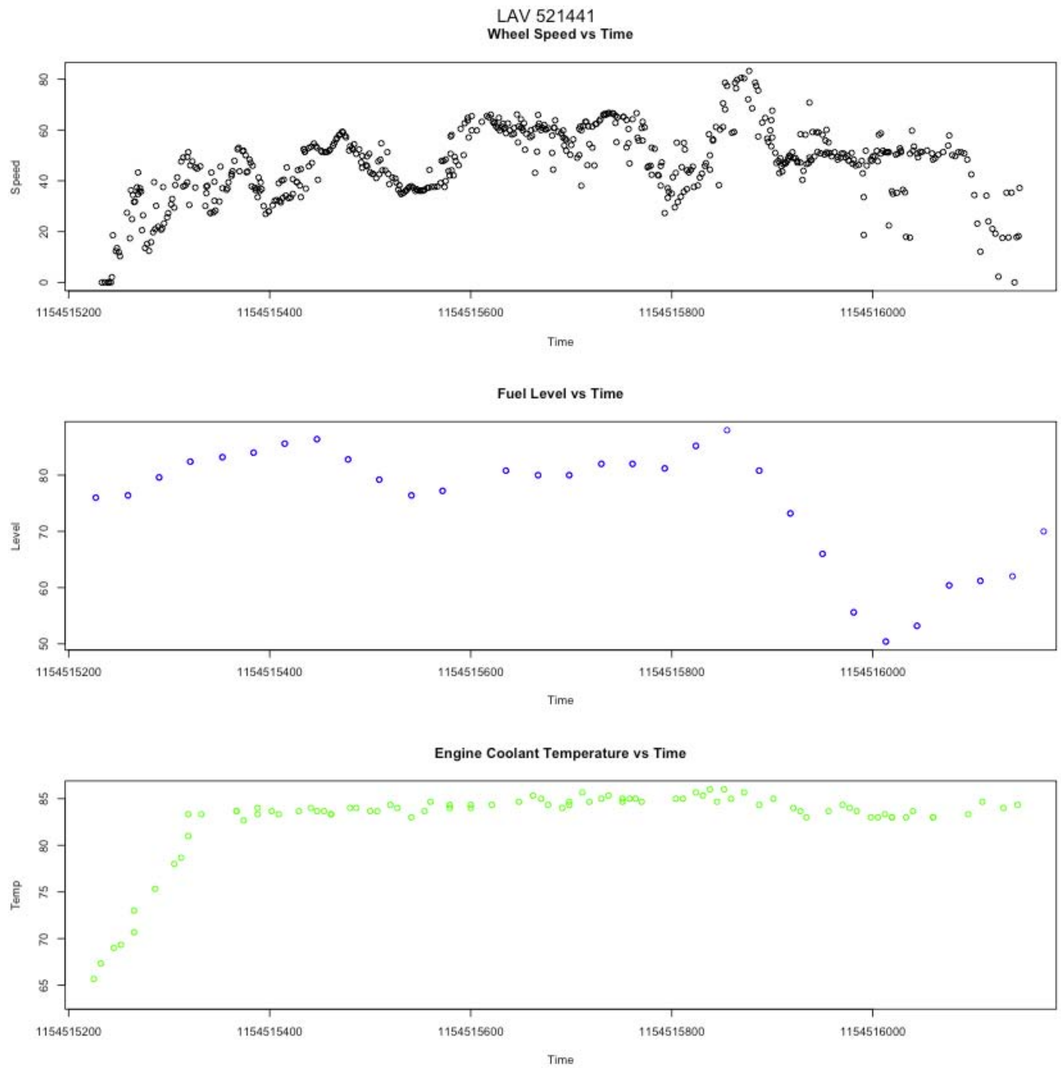

Figure 11.   LAV 521441 fuel level abnormality

3. LAV Number 521689

In the process of analyzing the data for this vehicle, an initial error is discovered that requires further sorting to correct before time-based analysis is performed. All the data are not recorded in chronological order. The second column in Figure 12 shows this trend of date fluctuations between several days that are not consecutive.

Since this data is not initially recorded chronologically, the data is sorted according to date to allow time-based, chronological analysis.

```
521689,2006-09-12 09:06:06.567000000,84,2057149706,0
521689,2006-09-01 14:34:01.527000000,84,8996829556,0
521689,2006-09-01 14:33:32.100000000,84,8968074492,0
521689,2006-09-12 09:06:07.567000000,84,2058142338,0
521689,2006-09-12 09:15:08.403000000,84,2586632902,0
521689,2006-09-12 09:15:09.420000000,84,2587616741,0
521689,2006-09-12 09:05:59.413000000,84,2050174903,0
521689,2006-09-12 09:15:55.293000000,84,2632451271,0
521689,2006-09-12 09:45:08.310000000,84,4345293476,0
521689,2006-08-31 15:21:44.413000000,84,244854763,0
521689,2006-08-31 15:21:46.420000000,84,246845889,0
521689,2006-08-31 15:21:47.403000000,84,247822889,0
```

Figure 12. LAV 521689 nonchronological data

During the dynamic analysis for this vehicle a second error is discovered. There are information gaps in the data reported by the wheel speed sensors. The upper plot in Figure 13 depicts this wheel speed sensor error. The plot should be recording data on a consistent basis, similar to the lower plot in Figure 13, which depicts the engine speed.

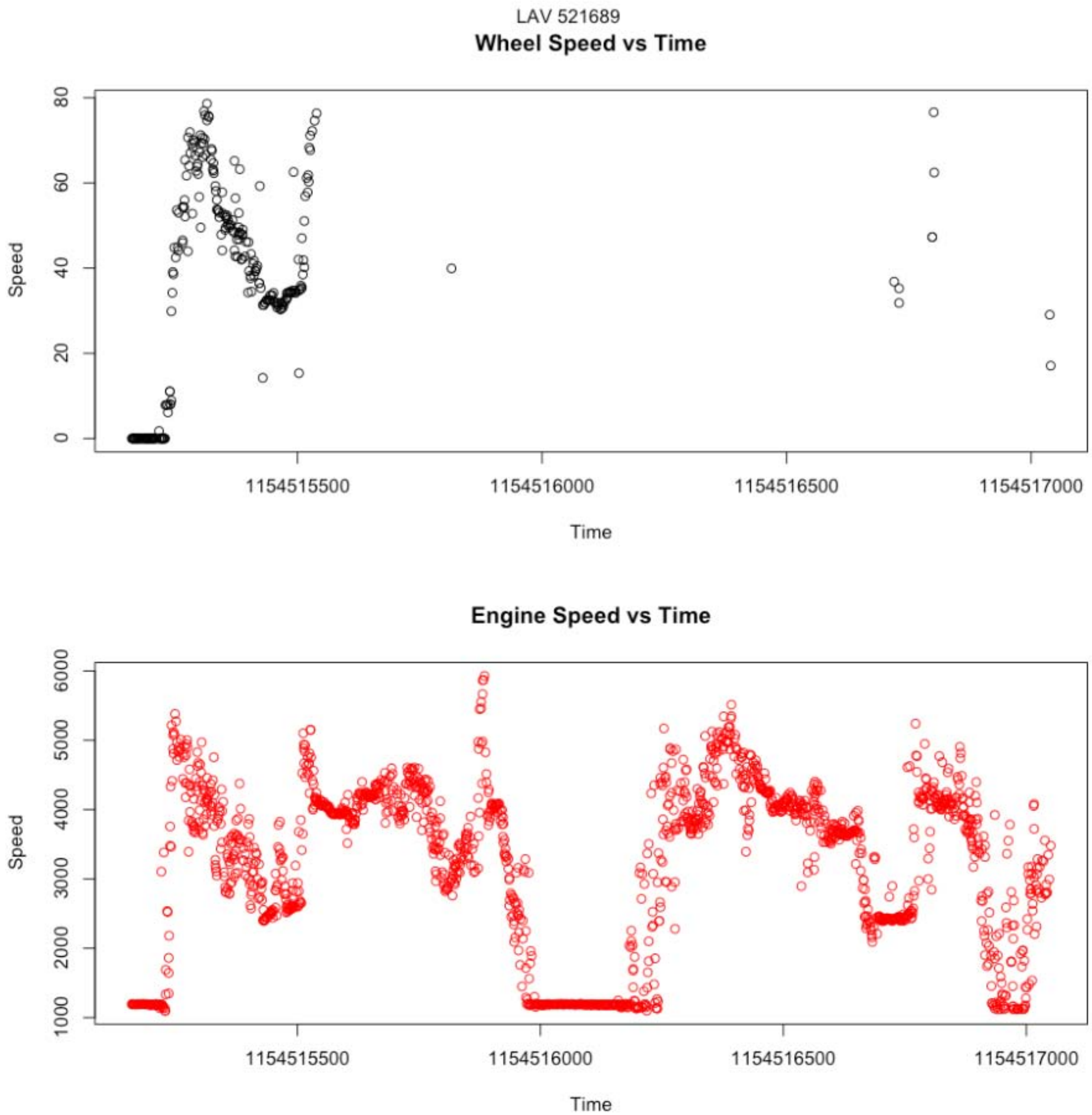

Figure 13. Information gaps

4. LAV Numbers 521366, 521749, 521417, 521516

In the process of analyzing the data for these vehicles, an error is discovered that requires further sorting to correct before time-based analysis is performed. All the data are not recorded in chronological order. The second column in Figure 14 shows this trend of date fluctuations between several days that are not consecutive.

Since this data is not initially recorded chronologically, the data is sorted according to date to allow time-based, chronological analysis.

```
521366 2006-09-07 14:33:25.867000000,84,411751765,0
521366 2006-09-14 15:10:06.180000000,84,750209967,0
521366 2006-09-07 14:33:29.583000000,84,415742810,0
521366 2006-09-14 15:10:32.727000000,84,777186891,0
521366 2006-09-14 15:10:06.180000000,84,750209967,0
521366 2006-09-14 15:10:32.727000000,84,777186891,0
521366 2006-08-30 08:27:27.483000000,84,1212163900,0
521366 2006-09-14 15:10:38.837000000,84,783170039,0
521366 2006-09-14 15:10:06.240000000,84,751194783,0
521366 2006-08-30 08:27:28.497000000,84,1213156532,0
521366 2006-08-30 08:27:27.483000000,84,1212163900,0
521366 2006-09-14 15:10:38.837000000,84,783170039,0
```

Figure 14. LAV 521366 nonchronological data

5. LAV Number 521563

During the analysis of the static data file for this vehicle, wheel speed sensor and fuel sensor errors are discovered. Although the change is minor, the fuel level vacillates between 85.6 and 86.0 with no vehicular motion or engine consumption (see lower plot in Figure 15). The upper plot in Figure 15 demonstrates a sporadic wheel speed sensor. The engine speed sensor, portrayed in the middle plot of Figure 15, records somewhat consistently while the wheel speed (upper plot) and fuel sensors (lower plot) do not.

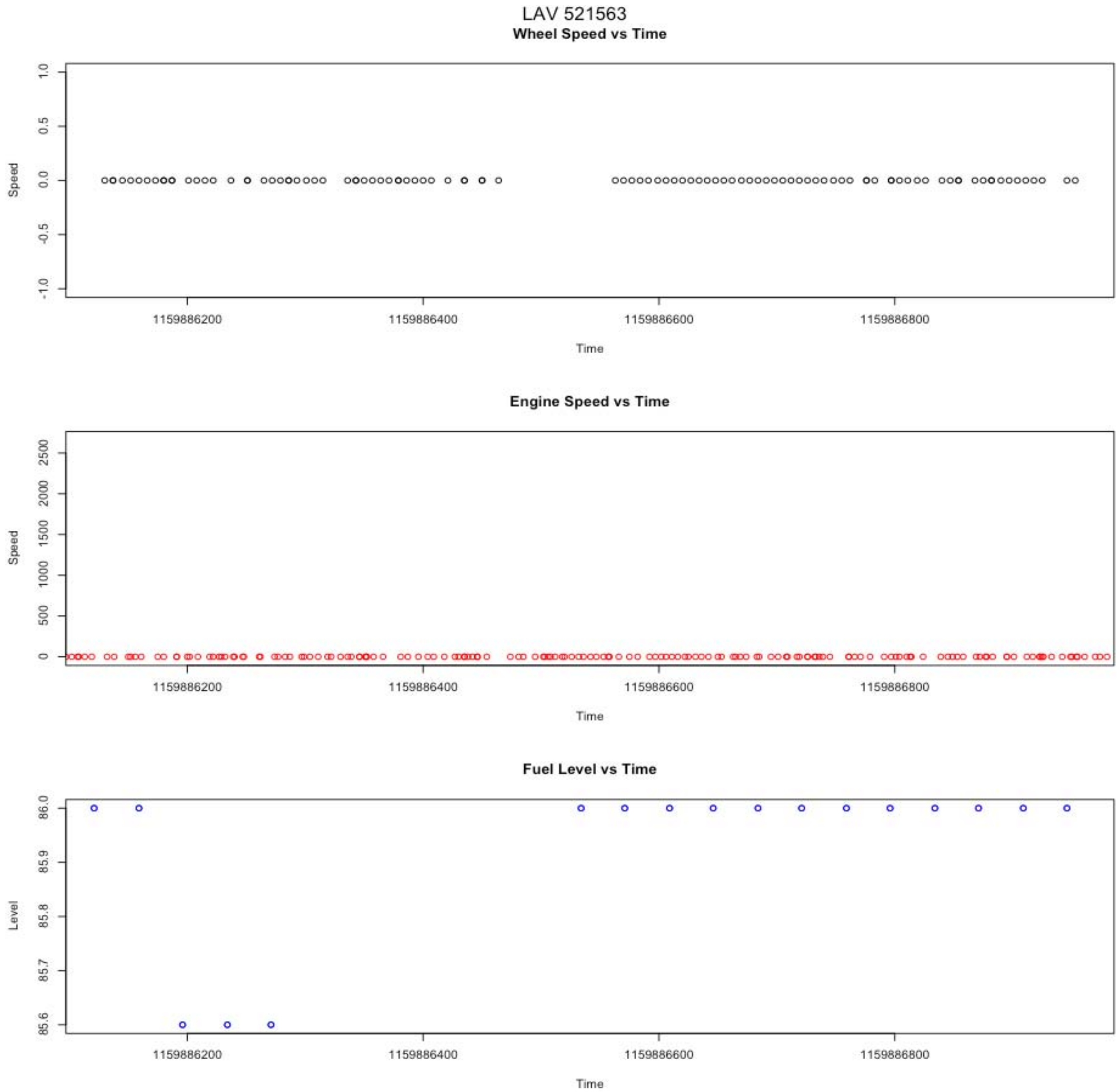

Figure 15. Wheel speed and fuel level inconsistencies

6. LAV Number 521485

This vehicle’s sensors record a sparse number of data points for fuel level (middle plot Figure 16) as well as for the fuel pump (lower plot Figure 16) when compared to the engine speed (upper plot Figure 16).

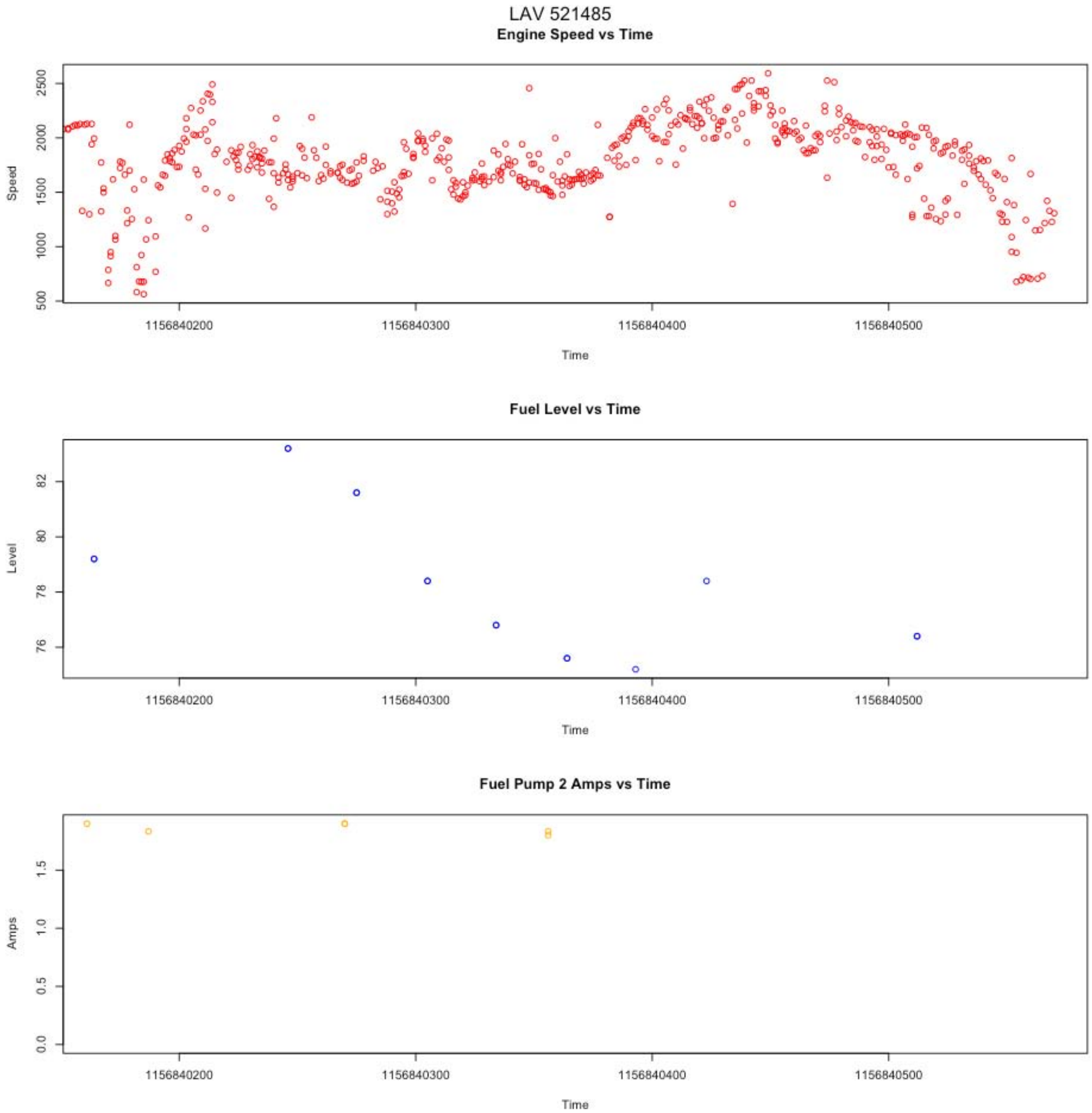

Figure 16. Sparse data points

7. LAV Number 521471

The only data recorded for this vehicle is stationary in nature and limited in frequency. The only analysis carried out is static analysis. Both upper and lower plots in Figure 17 depict the sparseness of the data. It should also be noted that while the vehicle did not move and the engine did not run, the engine coolant temperature sensor records a maximum value of 63 degrees Celsius. This is about 145 degrees Fahrenheit and is assumed to be incorrect considering the nonoperation of the vehicle. However, this is below the upper bound of the operating range, and thus is not included in the sensor reporting errors.

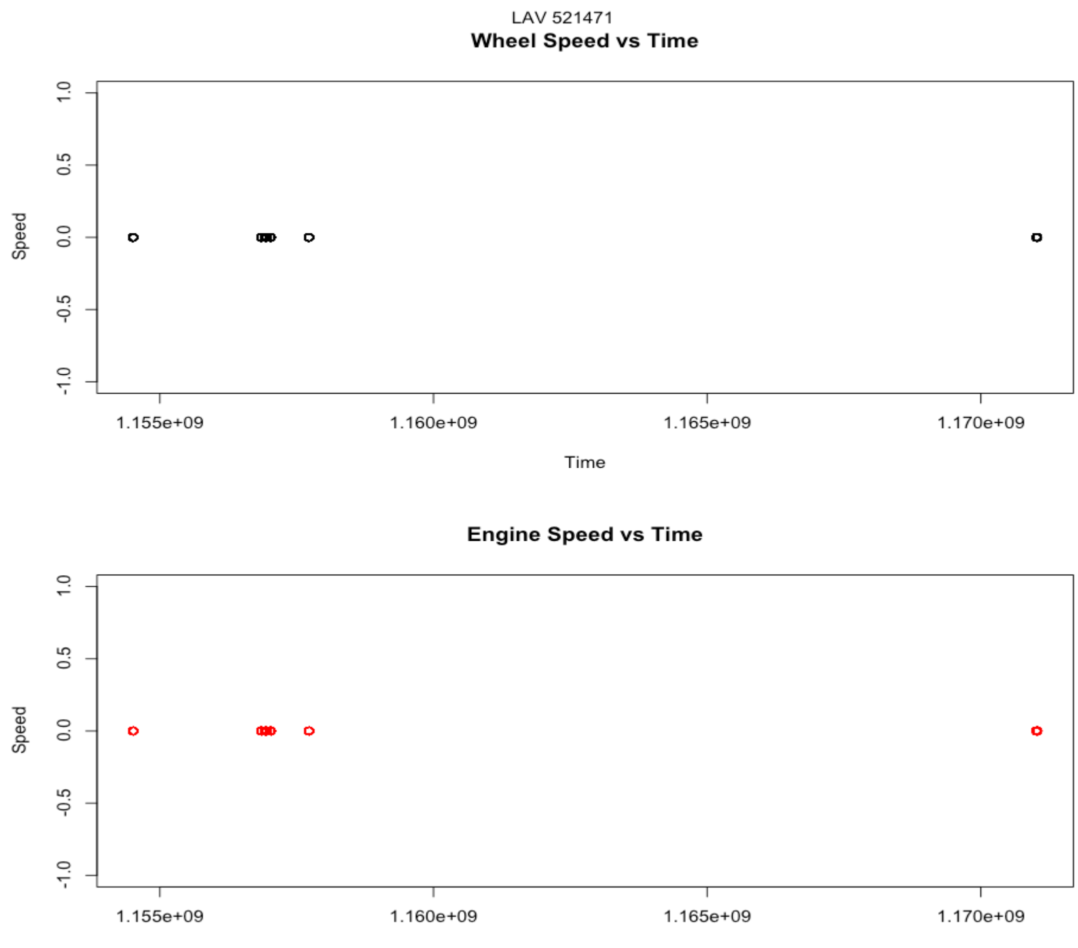

Figure 17. Data Sparseness.

8. Phase II Error Summary

The errors discovered during the analysis of the ten Phase II LAVs are depicted in Figure 18. The analysis carried out on the four Phase III LAVs is included in the following section.

Serial Number	Errors
521363	Fuel Level Sensor
521441	Fuel Level Sensor
521689	Non-Chronologic Data
	Wheel Speed Sensor
521366	Non-Chronologic Data
521749	Non-Chronologic Data
521563	Fuel Level Sensor
	Wheel Speed Sensor
521485	Fuel Level Sensor
	Fuel Pump Sensor
521471	Engine Coolant Temperature Sensor
	Sparse Data From All Sensors
521417	Non-Chronologic Data
521516	Non-Chronologic Data

Figure 18. Phase II error summary

C. PHASE III CORRECTED DATA ANALYSIS BY LAV SERIAL NUMBER

There are several major differences between the Phase II and Phase III analysis. The first major difference is the number of LAVs. Phase II consists of ten LAVs and Phase III consists of only four. Next, the analysis carried out in Phase II includes six sensors whereas in Phase III there are 23 sensors included. Another major difference between the two phases is sensors that directly affect other sensors. For example, the voltage output from the alternator should closely resemble the voltage measured from the batteries. Thus, the batteries are directly affected by the alternator. If performance within this alternator-battery system is degraded, this degraded performance will be reported by more than one sensor. Sensors on the alternator as well as the four batteries are evaluated and compared with each other.

The voltage is analyzed using a combined approach. The TM states that batteries wired in series have voltage between 24 and 28 volts. So, the voltage from batteries one and two is summed and analyzed together, and the voltage from batteries three and four is summed and analyzed together. If the system is operating correctly, the summed voltage from batteries one and two should closely resemble the summed voltage from batteries three and four, which should closely resemble the alternator voltage.

Another system analyzed is the alternator current. The current is measured from the alternator as well as at the batteries. Again, the alternator affects what the battery sensors report. The current measuring sensors already group batteries one and two together as well as three and four together, so no extra processing is required.

1. LAV Number 521661

The analysis for this vehicle reveals a problem with the engine hour sensor. The engine hours do not increase as the engine operates. The lower plot in Figure 19 depicts this trend. This plot shows the recorded engine hours by comparison with the engine speed (upper plot Figure 19), which is clearly operating during the time frame. This same trend is observed during static and dynamic operation. Even though the time frame in Figure 19 is less than ten minutes, Figure 19 represents the entire data file with one exception. The engine speed data file has one data point at 98,533,376 hours. Clearly, the sensor is not operating correctly.

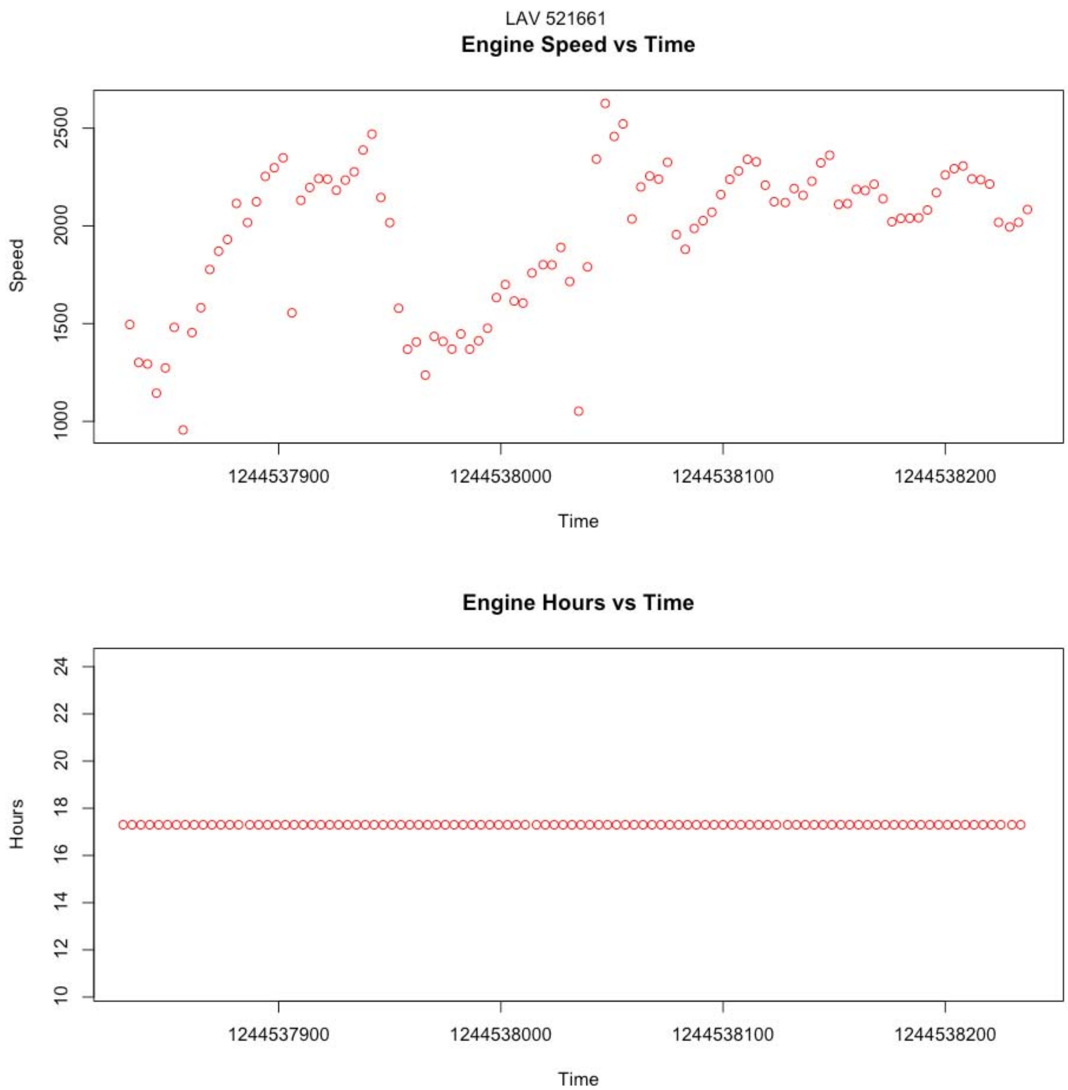

Figure 19. Engine hour sensor irregularity

2. LAV Number 521683

The overall data set for this vehicle does not contain enough moving segments to isolate for analysis. So, the analysis carried out is assumed stationary and includes the entire file.

All of the sensors related to the GPS do not operate consistently on this vehicle. These sensors include the Compass Heading (165), GPS Vehicle Speed (517), Latitude (584) and Longitude (585).

The battery one voltage sensor (96) also does not report data values at several time periods, while all other batteries and the alternator do report values.

There are no data points recorded for the Battery Temperature (1800).

The wheel speed plot depicted in the upper plot of Figure 20 shows several data points over 150 km/h, while the odometer (lower plot in Figure 20) only records movement equal to half of a kilometer. It is unlikely these wheel speeds are accurate, given the distance recorded as well as the lack of recorded wheel speeds. In other words, there are no increasing data points either accelerating to 150 km/h or decelerating from 150 km/h.

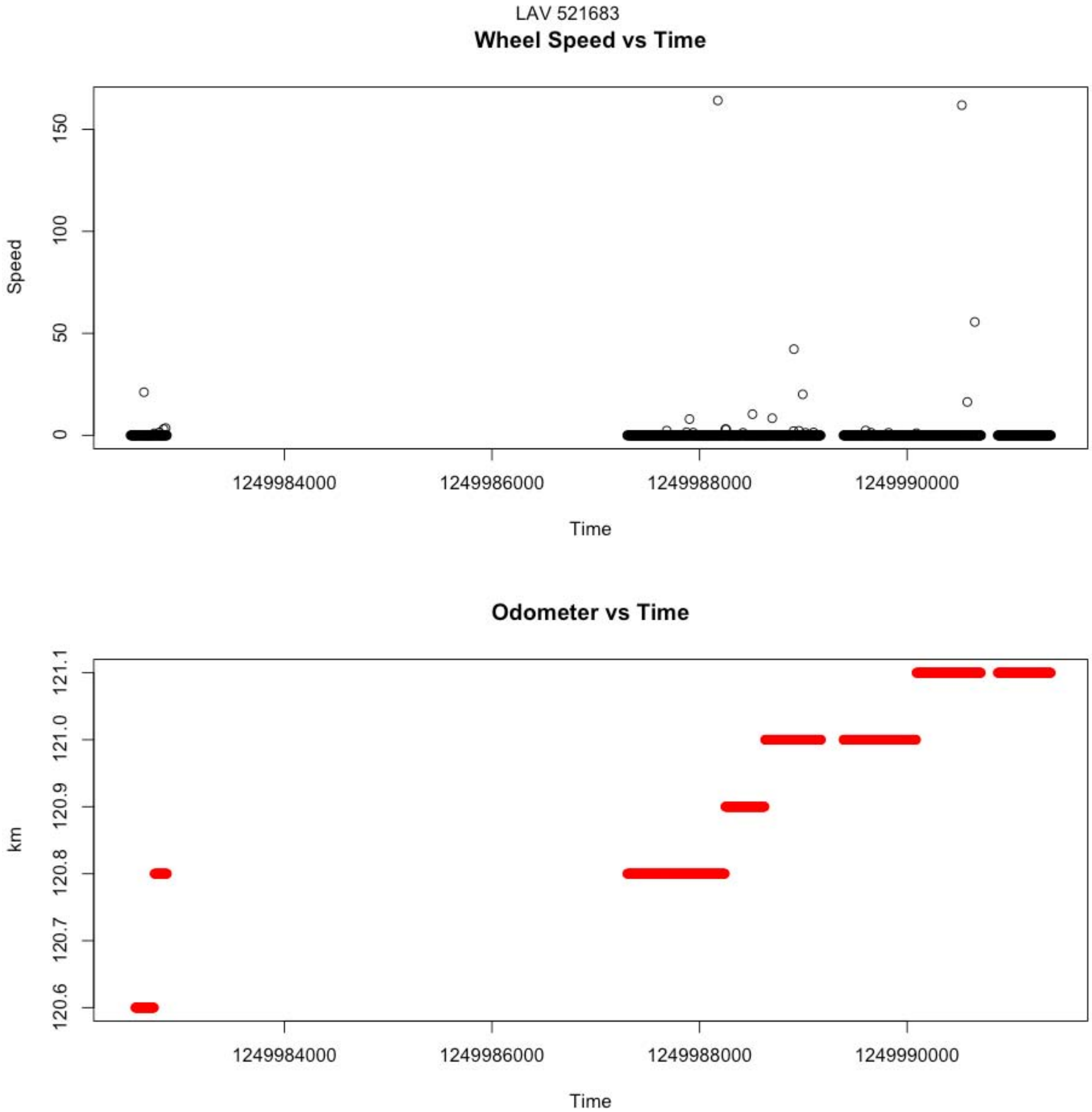

Figure 20. Wheel speed anomalies

3. LAV Number 521753

Several patterns emerge from the LAV 521753 data set that involve wheel speed. The first concerns how wheel speed relates to engine speed. The upper plot in Figure 21 depicts an unusually smooth decrease in wheel speed while the engine speed sensor (middle plot in Figure 21) records values below normal idle. The second pattern is also depicted in Figure 21 and shows that during recorded wheel speeds (upper plot in Figure 21), the odometer (lower plot in Figure 21) does not record any movement. Since the wheel speed data for this time period do not appear to be reliable, a different time frame is used for analysis.

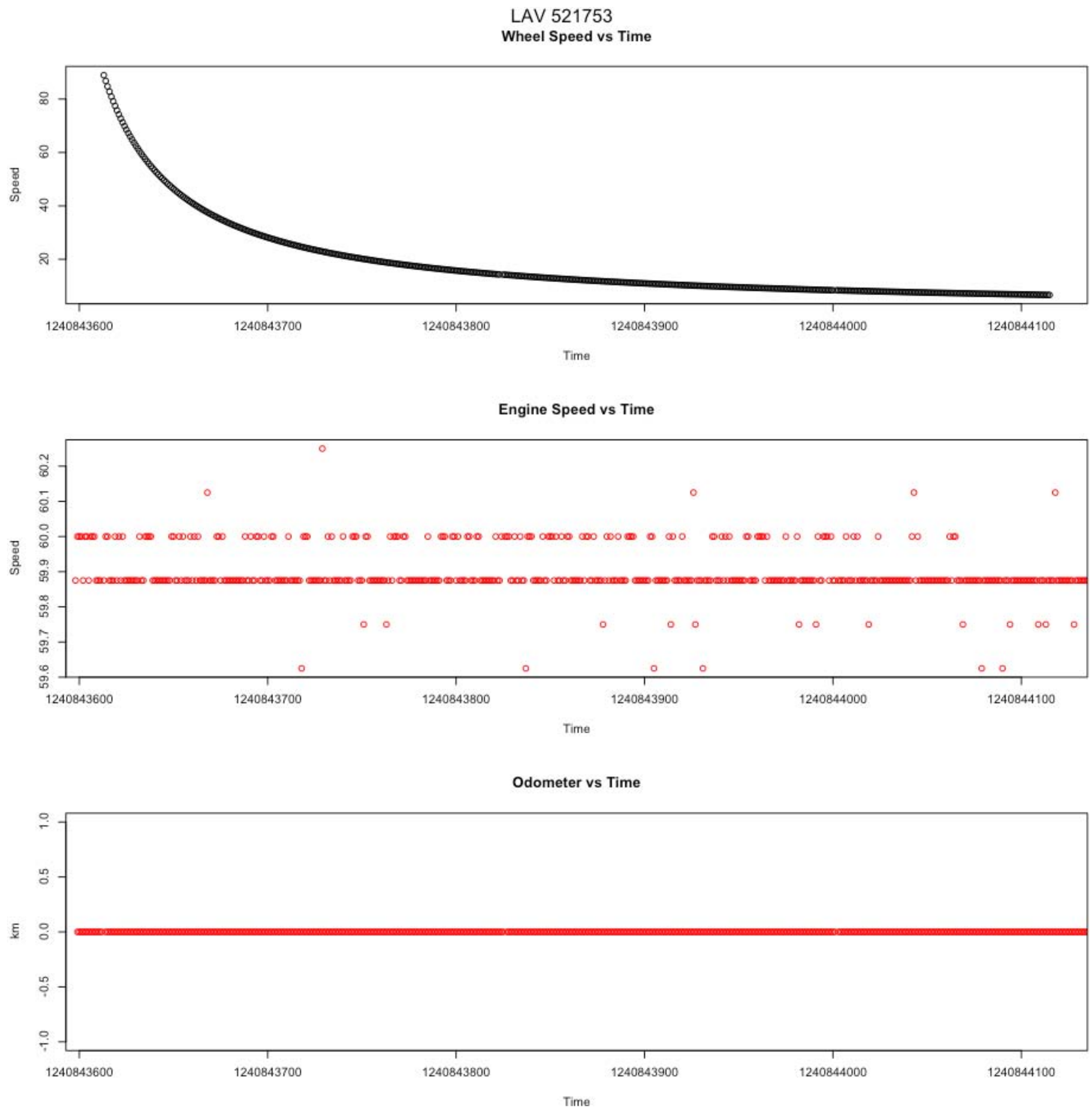

Figure 21. Decreasing wheel speed without odometer change

4. LAV Number 521767

The primary concern with the data from this vehicle is missing data. Figure 22 depicts how all the sensors did not record data at the same time. Since there are multiple periods of time where various sensors do not record data when others do, a time period is chosen for analysis that includes the most data available. However, the dynamic analysis period is missing data from the following sensors: (1) Compass Heading (SPN 165), (2) GPS Vehicle Speed (SPN 517), (3) Latitude (SPN 584) and (4) Longitude (SPN 518). The static analysis period is missing data from the following sensors: (1) Compass Heading (SPN 165), (2) GPS Vehicle Speed (SPN 517), (3) Battery Temperature (SPN 1800), (4) Battery 1-2 Current (SPN 9002), (5) Battery 4 Voltage (SPN 9005), (6) Battery 3-4 Current (SPN 19002), (7) Battery 3 Voltage (SPN 19005), (8) Battery 2 Voltage (SPN 29005) and (9) Battery 1 Voltage (SPN 39005).

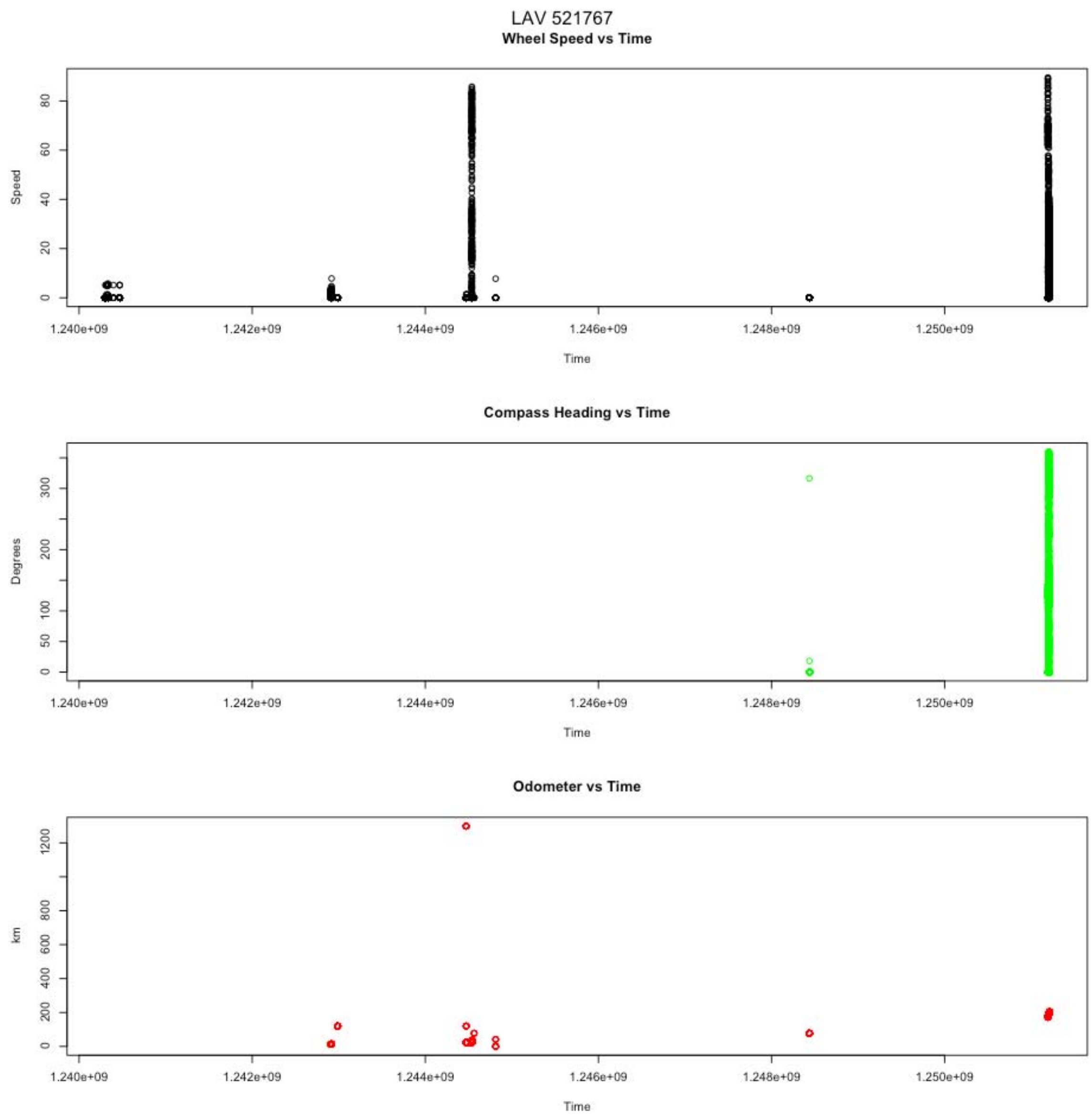

Figure 22. Missing data

5. Phase III Error Summary

The errors discovered during the analysis of the four Phase III LAVs are depicted in Figure 23.

Serial Number	Errors
521661	Engine Hours Sensor
521683	Battery One Voltage Sensor
	Battery Temperature Sensor
	Compass Heading Sensor
	GPS Vehicle Speed Sensor
	Latitude Sensor
	Longitude Sensor
	Missing Dynamic Data
	Wheel Speed Sensor
521753	Wheel Speed Sensor
	Odometer Sensor
521767	Missing Data

Figure 23. Phase III error summary

D. PHASE II UNCORRECTED VERSUS PHASE III CORRECTED

In order to compare Phase II data with Phase III data, two comparisons are used. The first includes comparing the ratio of data points that fall within normal operating parameters. The second includes a hypothesis test using a Kruskal-Wallis test on several quantiles of data from sensors that are shared by both phases.

1. Data Points Within Normal Operating Parameters

Since there is no baseline from which to measure accuracy of the sensors, normal operating parameters are used for comparison. Appendix B depicts the operating parameters as established by the technical manuals. These parameters establish an upper and lower bound for the normal operating range. However, there are a few sensors that do not have a normal operating range. For example, a single upper bound for wheel speed is difficult to establish, so an upper bound is not included, thus prohibiting comparison analysis on this sensor. Also, the odometer and engine hours do not have bounds and thus do not have a normal operating range. The battery temperature range is not established using the technical manual and is also not included. The percentage used for the analysis is calculated using the data points that fall within this range (see Figure 24). The result of all calculated ratios is depicted in Figure 25.

$$\frac{\textbf{Total Data Points Within Normal Operating Bounds}}{\textbf{Total Data Points}} \times 100$$

Figure 24. Normal operating parameter ratio

Sensor	Phase II (un)	Phase III
96	34	23
110	94	13
115		100
165		100
167		66
190	98	100
584		100
585		100
1087		51
1088		50
9002		55
15092	81	25
15093		21
19002		82
Batt 1-2		46
Batt 3-4		81

Figure 25. Sensor percentages within normal bounds

2. Hypothesis Test

In order to determine if there is a statistical difference between Phase II and Phase III data, a Kruskal-Wallis test (Ugarte, 436) is carried out. The statistic used in the test corresponds to the upper and lower bounds.

In order to establish whether there is a statistical difference between sensor values outside normal parameters, quantiles are used. Keeping in mind that phase comparison only includes four sensors, quantiles are used as a measure of how far outside the normal operating parameters the data is distributed. Sensors for the fuel level (96), engine coolant (110) and engine speed (190) only report values inside and above normal operating parameters. So, the 90th, 95th, 97th and 99th quantiles are evaluated. For the fuel pump voltage sensor (15092), which reports values above, within and below normal operating parameters, the 1st, 3rd, 5th, 10th, 90th, 95th, 97th and 99th quantiles are used.

The null hypothesis assumes there is no statistical difference between the quantiles of either phase. The alternative assumes that there is a statistical difference between the phases, thereby producing a two-sided test (see Figure 26).

$$H_0 : \text{Phase II Quantiles} = \text{Phase III Quantiles}$$
$$H_1 : \text{Phase II Quantiles} \neq \text{Phase III Quantiles}$$

Figure 26. Hypothesis test for quantiles

The p values from the Kruskal-Wallis tests (Ugarte, 436) are depicted in Figure 27. At the 95% level, there is evidence to suggest a difference between the engine speed sensors at all quantile levels evaluated. There is also evidence to suggest a difference between the fuel pump sensors in the first quantile at the 95% level as well.

	1%	3%	5%	10%	90%	95%	97%	99%
Fuel Level (Sensor 96)	n/a	n/a	n/a	n/a	0.059	0.104	1.00	0.747
Engine Coolant Temperature (Sensor 110)	n/a	n/a	n/a	n/a	0.005	0.005	0.005	0.005
Engine Speed (Sensor 190)	n/a	n/a	n/a	n/a	0.123	0.355	0.537	0.877
Fuel Pump (Sensor 15092)	0.004	0.058	0.058	1.00	0.437	0.437	0.351	0.876

Figure 27. Kruskal-Wallis p values comparing Phase II with Phase III data

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IV. CONCLUSIONS AND RECOMMENDATIONS

The analysis presented in this thesis is intended to provide a better understanding and overview of the combined efforts of many organizations. These organizations primarily include PMLAV, NSWC Crane, Indiana, Delphi and Solidica. To this end, this thesis answers several questions related to data quality and overall sensor program performance.

In response to the question of whether the processes by which data are collected are reporting values within normal operating parameters, the answer is, in general, yes. The average amount of data reported within normal operating parameters for Phase II is about 77%. Keep in mind that normal operating parameters can only be applied to four of the six sensors analyzed from Phase II. About 63% of the data reported from Phase III is within normal operating parameters. This percentage includes the 16 sensors for which normal operating parameters could be applied.

Since a baseline does not exist for the sensor data, the extent to which the accuracy could be measured is restricted to normal operating ranges. However, it is recommended that any future work include a baseline in order to make a definitive statement as to the accuracy of the sensor data.

Once the accuracy of the data is determined, the question concerning specific sensor error introduction can be answered. As it stands with this thesis, the location of specific error introduction cannot be discerned. However, it was discovered that the data, at some point within the data collection process for Phase II, is not in chronological order. Chapter III depicts the chronological errors discovered. It is recommended that a comparison be made between the OBC data, prior to wireless transmission, and the data recorded in the local and enterprise servers after wireless transmission. Further, this program would greatly benefit from direct data transfer from local to enterprise server. Currently, the data cannot be transferred directly between LAVTC and NSWC Crane. The process by which data is transferred may introduce an opportunity for error that could be mitigated by the direct transfer of data.

Comparing the two phases is not as thorough as one would desire because there are only four sensors, out of more than 30, for which a direct phase comparison can be made. However, direct phase comparison can be made using the aforementioned four sensors. This comparison determined that there is a statistical difference between the reported values from the engine coolant temperature sensors. Also, there is a significant difference between the reported values from the fuel pump sensors at the first quantile. This process is further complicated by the fact that Phases II and III were managed by two different entities, Delphi and Solidica, respectively. The primary recommendation in this area is consolidation, which means using all data collection devices together for the benefit of the overall program. Currently, there are ten LAVs outfitted with Phase II sensors and four LAVs outfitted with Phase III sensors. Also, there are LAVs outfitted with EPLS sensors. The quantity and extent of the EPLS outfitted LAVs are not considered in the thesis. However, it should be noted that the EPLS LAVs are managed by the program manager for Autonomic Logistics and all other LAVs are managed by the program manager for Light Armored Vehicles.

The primary similarity between the two data sets involves data correction. The methods used by both Delphi and Solidica to correct the sensor data are proprietary in nature. It is recommended that the data cleansing and correcting methods used on these, and future projects, be unrestricted for official use by the owning entity.

In order for future studies to be fruitful, it is recommended that any future experiments be designed with consideration given to appropriate mathematical measures of effectiveness. Although the format for this experiment was a valid one, the principal data required was never collected. Thus, a true measure of effectiveness was never established.

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APPENDIX A

SENSOR DESCRIPTIONS FROM ENTERPRISE SERVER DATA

```
SPN,PGN,Name,Units,NaN
84,65265,Wheel-Based Vehicle Speed,km/h,False
96,65276,Fuel Level,%,False
110,65262,Engine Coolant Temperature,C,False
115,65271,Alternator Current,A,False
165,65256,Compass Bearing,deg,False
167,65271,Charging System Potential (Voltage),V,False
190,61444,Engine Speed,rpm,False
245,65248,Total Vehicle Distance,km,False
247,65253,Engine Total Hours of Operation,hr,False
517,65256,Navigation-Based Vehicle Speed,km/h,False
584,65267,Latitude,deg,False
585,65267,Longitude,deg,False
1087,65198,Service Brake Circuit 1 Air Pressure,kPa,False
1088,65198,Service Brake Circuit 2 Air Pressure,kPa,False
1800,65104,Battery 4 Temperature,C,False
1801,65189,Battery 3 Temperature,C,False
9000,65296,SOC Batt4,A,False
9001,65296,SOH Batt4,A,False
9002,65296,Current BT1-2,A,False
9003,65296,12VPotential,V,False
9004,65296,24VPotential,V,False
9005,65297,VBatt4,%,False
11800,65288,Temp Batt2,%,False
11801,65288,Temp Batt1,%,False
15092,65491,Fuel Pump #1 Current,A,False
15093,65491,Fuel Pump #2 Current,A,False
19000,65280,SOC Batt3,%,False
19001,65280,SOH Batt3,%,False
19002,65296,Current BT3-4,A,False
19005,65280,VBatt3,V,False
29000,65280,SOC Batt2,%,False
29001,65280,SOH Batt2,%,False
29005,65297,VBatt2,V,False
39000,65280,SOC Batt3,%,False
39001,65280,SOH Batt1,%,False
39005,65297,VBatt1,A,False
```

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APPENDIX B

OPERATING RANGES AS ESTABLISHED IN THE TECHNICAL MANUALS

SPN	Sensor Description	Phase II	Phase III	Lower Bound	Upper Bound	Units	TM	Section/Paragraph	Page
84	Wheel speed	Yes	Yes	0		km/h	N/A		
96	Ratio of fuel level to volume of tank	Yes	Yes	0	71	gal	08594B-10/2	1-8	1-15
110	Engine Coolant Temperature	Yes	Yes	0	100	C	08594B-10/2	2-2	2-11
115	Alternator Current	No	Yes	0	280	A	08594B-10/2	Electrical System	1-18
165	Compass Heading	No	Yes	0	360	deg	N/A		
167	Alternator Voltage	No	Yes	0	28	V	08594B-10/2	Electrical System	1-18
190	Engine speed	Yes	Yes	0	2800	RPM	08594B-10/2	5	2-12
245	Odometer	No	Yes			km	N/A		
247	Engine Hours	No	Yes			hours	N/A		
517	GPS Vehicle Speed	No	Yes			km/h	N/A		
584	Latitude	No	Yes	0	90	deg	N/A		
585	Longitude	No	Yes	-180	0	deg	N/A		
1087	Air Pressure 1	No	Yes	689.5	827.4	kPa	08594B-10/2	8 & 9	2-13
1088	Air Pressure 2	No	Yes	689.5	827.4	kPa	08594B-10/2	8 & 9	2-13
1800	Battery temperature	Yes	Yes			deg			
9002	Battery 3-4 Current	No	Yes	0	280	A	08594B-10/2	Electrical System	1-18
9005	Battery 4 Voltage	No	Yes	11.8	12.2	V	08594B-10/2	Electrical System	1-18
15092	Fuel Pump 1 (pump 2 in phase II)	Yes	Yes	0	2	A	08594B-20-4-1	9	11-16
15093	Fuel Pump 2	No	Yes	0	2	A	08594B-20-4-1	9	11-16
19002	Battery 3-4 Current	No	Yes	0	280	A	08594B-10/2	Electrical System	1-18
19005	Battery 3 Voltage	No	Yes	11.8	12.2	V	08594B-10/2	Electrical System	1-18
29005	Battery 2 Voltage	No	Yes	11.8	12.2	V	08594B-10/2	Electrical System	1-18
39005	Battery 1 Voltage	No	Yes	11.8	12.2	V	08594B-10/2	Electrical System	1-18
	Batt 1 & 2	No	Yes	24	28	V	08594B-10/2	1-17	1-28
	Batt 3 & 4	No	Yes	24	28	V	08594B-10/2	1-17	1-28

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APPENDIX C

SAMPLE OF DATA COLLECTED FROM PHASE II

Moving											
Vehicle	SPN	Description	Data Minimum Value	Lower Bound	Data Maximum Value	Upper Bound	Mean	Median	Units	Total Data Points	Percent in Range
521363	84	Wheel Based Vehicle Speed	0	0	109.4		24.23	1.7	km/h	7500	n/a
	96	Fuel Level	25.2	0	62.8	71	31.1	25.2	gal	150	1.000
	110	Engine Coolant Temperature	29	0.00	87	100	47.5	32	C	7500	1.000
	190	Engine Speed	0	0	2923	2800	1145	691.3	RPM	7500	0.989
	1800	Battery Temperature	26		32		29.25	29	C	7500	n/a
	15092	Fuel Pump 2	-0.1	0	1.6	2	-0.025	-0.1	A	7500	0.047

Stationary											
Vehicle	SPN	Description	Data Minimum Value	Lower Bound	Data Maximum Value	Upper Bound	Mean	Median	Units	Total Data Points	Percent in Range
521363	84	Wheel Based Vehicle Speed	0	0	0		0	0	km/h	2301	n/a
	96	Fuel Level	49.2	0	52	71	49.58	49.6	gal	75	1
	110	Engine Coolant Temperature	80	82.20	85	100	82.82	83	C	333	1
	190	Engine Speed	0	0	0	2800	0	0	RPM	2248	1
	1800	Battery Temperature	28		28		28	28	C	333	n/a
	15092	Fuel Pump 2	-0.1	0	-0.1	2	-0.1	-0.1	A	77	0

Entire File											
Vehicle	SPN	Description	Data Minimum Value	Lower Bound	Data Maximum Value	Upper Bound	Mean	Median	Units	Total Data Points	Percent in Range
521363	84	Wheel Based Vehicle Speed	0	0	109.4		4.29	0	km/h	42414	n/a
	96	Fuel Level	25.2	0	62.8	71	31.1	25.2	gal	3704	1.000
	110	Engine Coolant Temperature	29	0.00	87	100	45.2	32	C	9080	1.000
	190	Engine Speed	0	0	2923	2800	258	0	RPM	41712	0.998
	1800	Battery Temperature	26		32		29.5	29	C	9100	n/a
	15092	Fuel Pump 2	-0.1	0	1.6	2	-0.047	-0.1	A	10720	0.033

Quantiles											
Vehicle	SPN	Description	1%	3%	5%	10%		90%	95%	97%	99%
521363	84	Wheel Based Vehicle Speed									
	96	Fuel Level						48.8	53.2	54.8	62
	110	Engine Coolant Temperature						83	84.00	85	85
	190	Engine Speed						688	1632	2024	2587
	1800	Battery Temperature									
	15092	Fuel Pump 2	-0.1	-0.1	-0.1	-0.1		-0.1	-0.1	1.5	1.5

SAMPLE OF DATA COLLECTED FROM PHASE III

Moving											
Vehicle	SPN	Description	Data Minimum Value	Lower Bound	Data Maximum Value	Upper Bound	Mean	Median	Units	Total Data Points	Percent in Range
521661	84	Wheel Based Vehicle Speed	16.7		83.44		49.5	42.9	km/h	101	n/a
	96	Fuel Level	28.8		99.2	71	90	94	gal	101	0.0495
	110	Engine Coolant Temperature	171		178	100	174.1	173	C	101	0
	115	Alternator Current	6		6	280	6	6	A	101	1
	165	Compass Heading	101.3	0.00	246.2	360	154.3	142.2	deg	102	1
	167	Alternator Voltage	28.6	0.00	28.8	28	28.7	28.7	V	101	0
	190	Engine Speed	955.9		2627	2800	1957	2082	RPM	101	1
	245	Odometer	63.6		68.3		65.3	65	km	101	n/a
	247	Engine Hours	17.3		17.3		17.3	17.3	hour	101	n/a
	517	GPS Vehicle Speed	17.5		87.7		51.2	44.6	km/h	102	n/a
	584	Latitude	33.4	0	33.4	90	33.4	33.4	deg	102	1
	585	Longitude	-117.6	-180	-117.6	180	-117.5	-117.6	deg	102	1
	1087	Tank 1 Air Pressure	824	689.5	952	827.4	885.7	904	kPa	102	0.0294
	1088	Tank 2 Air Pressure	824	689.5	952	827.4	887.4	904	kPa	102	0.0196
	1800	Battery Temperature	34		35		34.9	35	C	102	n/a
	9002	Battery 1-2 Current	11.2		14.7	280	13.1	13.2	A	102	1
	9005	Battery 4 Voltage	34	0	35	12	34.9	35	V	102	n/a
	15092	Fuel Pump 1 (in phase II this is Fuel Pump 2)	0.9	0	0.9	2	0.900	0.9	A	81	1
	15093	Fuel Pump 2	-3.3	0	-3.3	2	-3.3	-3.3	A	81	0
	19002	Battery 3-4 Current	8.8		10.3	280	9.6	9.7	A	102	1
	19005	Battery 3 Voltage	14.2	0	14.3	12	14.2	14.3	V	102	n/a
	29005	Battery 2 Voltage	14	0	14	12	14	14.1	V	102	n/a
	39005	Battery 1 Voltage	14.3	0	14.4	12	14.4	14.4	V	102	n/a
		Batt 1 & 2	28.3	24	28.5	28	28.4	28.4		102	0
		Batt 3 & 4	48.25	24	49.3	28	49.2	49.3		102	0

Stationary												
Vehicle	SPN	Description	Data Minimum Value	Lower Bound	Data Maximum Value	Upper Bound	Mean	Median	Units	Total Data Points	Percent in Range
521661	84	Wheel Based Vehicle Speed	0		0		0	0	km/h	51	n/a
	96	Fuel Level	99.2		99.2	71	99.2	99.2	gal	51	0
	110	Engine Coolant Temperature	105		116	100	110.5	111	C	51	0
	115	Alternator Current	16		16	280	16	16	A	51	1
	165	Compass Heading	0	0.00	0	360	0	0	deg	51	1
	167	Alternator Voltage	28.6	0.00	28.7	28	28.7	28.7	V	51	0
	190	Engine Speed	587.6		631.8	2800	612	613.9	RPM	51	1
	245	Odometer	59.3		59.3		59.3	59.3	km	51	n/a
	247	Engine Hours	17.3		17.3		17.3	17.3	hour	50	n/a
	517	GPS Vehicle Speed	0		0		0	0	km/h	51	n/a
	584	Latitude	33.4	0	33.4	90	33.4	33.4	deg	51	1
	585	Longitude	-117.5	-180	-117.5	180	-117.5	-117.5	deg	51	1
	1087	Tank 1 Air Pressure	880	689.5	960	827.4	933	936	kPa	50	0
	1088	Tank 2 Air Pressure	880	689.5	960	827.4	933.8	936	kPa	50	0
	1800	Battery Temperature	33		33		33	33	C	51	n/a
	9002	Battery 1-2 Current	17.9		23.9	280	21.1	19.9	A	51	1
	9005	Battery 4 Voltage	33	n/a	33	n/a	33	33	V	51	n/a
	15092	Fuel Pump 1 (in phase II this is Fuel Pump 2)	0.9	0	0.9	2	0.900	0.9	A	41	1
	15093	Fuel Pump 2	-3.3	0	-3.3	2	-3.3	-3.3	A	41	0
	19002	Battery 3-4 Current	11.6		13.8	280	12.4	12.3	A	51	1
	19005	Battery 3 Voltage	14.2	n/a	14.3	n/a	14.2	14.3	V	51	n/a
	29005	Battery 2 Voltage	13.8	n/a	14.1	n/a	13.9	13.9	V	51	n/a
	39005	Battery 1 Voltage	14.4	n/a	14.6	n/a	14.5	14.6	V	51	n/a
		Batt 1 & 2	28.35	24	28.45	28	28.41	28.4	V	51	0
		Batt 3 & 4	47.2	24	47.3	28	47.2	47.3	V	51	0

Entire File											
Vehicle	SPN	Description	Data Minimum Value	Lower Bound	Data Maximum Value	Upper Bound	Mean	Median	Units	Total Data Points	Percent in Range
521661	84	Wheel Based Vehicle Speed	0		174.2		14.9	8.37	km/h	26192	n/a
	96	Fuel Level	0		99.2	71	86.6	90.8	gal	26221	0.105
	110	Engine Coolant Temperature	0		195	100	160.6	173	C	26220	0.021
	115	Alternator Current	0		179	280	5.99	2	A	26215	1
	165	Compass Heading	0	0.00	359.9	360	116.8	89.7	deg	26156	1
	167	Alternator Voltage	0	0.00	29.6	28	27.8	28.5	V	26217	0.154
	190	Engine Speed	0		8173	2800	1057	1044	RPM	26188	0.996
	245	Odometer	14.3		2048		1435	1575	km	26196	n/a
	247	Engine Hours	17.3		9.8x10^7		3828	71.6	hour	26201	n/a
	517	GPS Vehicle Speed	0		95.9		15.6	8.6	km/h	26157	n/a
	584	Latitude	33.2	0	33.4	90	33.3	33.3	deg	26156	1
	585	Longitude	-117.6	-180	-117.3	180	-117.5	-117.5	deg	26155	1
	1087	Tank 1 Air Pressure	0	689.5	992	827.4	760.3	872	kPa	26204	0.215
	1088	Tank 2 Air Pressure	0	689.5	1688	827.4	762	872	kPa	26205	0.204
	1800	Battery Temperature	30		43		37.5	37	C	2068	n/a
	9002	Battery 1-2 Current	-823.3		411.6	280	9.69	5.2	A	26420	0.845
	9005	Battery 4 Voltage	8	0	14.7	12	14	14.4	V	26354	n/a
	15092	Fuel Pump 1 (in phase II this is Fuel Pump 2)	-9.4	0	3.2	2	-2.280	-2.4	A	25798	0.032
	15093	Fuel Pump 2	-9.5	0	3.1	2	-2.16	-2.25	A	25799	0.005
	19002	Battery 3-4 Current	-306.5	0	162.1	280	5.6	3.9	A	26424	0.845
	19005	Battery 3 Voltage	7.1	0	14.7	12	13.7	13.9	V	26353	n/a
	29005	Battery 2 Voltage	7.85	0	14.9	12	13.9	14.2	V	26358	n/a
	39005	Battery 1 Voltage	7.25	0	14.9	12	13.8	14.1	V	26355	n/a
		Batt 1 & 2	18.1	24	29.1	28	27.7	28.3	V	26355	0.086
		Batt 3 & 4	18.05	24	29.1	28	27.7	28.3	V	26355	0.856

Quantiles											
Vehicle	SPN	Description	1%	3%	5%	10%		90%	95%	97%	99%
521661	84	Wheel Based Vehicle Speed									
	96	Fuel Level						98.8	99.2	99.2	99.2
	110	Engine Coolant Temperature						176	180	182	186
	115	Alternator Current									
	165	Compass Heading									
	167	Alternator Voltage									
	190	Engine Speed						1993.4	2177	2293	2508.2
	245	Odometer									
	247	Engine Hours									
	517	GPS Vehicle Speed									
	584	Latitude									
	585	Longitude									
	1087	Tank 1 Air Pressure									
	1088	Tank 2 Air Pressure									
	1800	Battery Temperature									
	9002	Battery 1-2 Current									
	9005	Battery 4 Voltage									
	15092	Fuel Pump 1 (in phase II this is Fuel Pump 2)	-4.8	-2.45	-2.45	-2.45		-2.2	-2.2	0.9	0.9
	15093	Fuel Pump 2									
	19002	Battery 3-4 Current									
	19005	Battery 3 Voltage									
	29005	Battery 2 Voltage									
	39005	Battery 1 Voltage									
		Batt 1 & 2									
		Batt 3 & 4									

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